

Apparatus Comprising a Micromechanical Resonator

Field of the Invention

[0001] The present invention relates to micromechanical resonators.

Background of the Disclosure

[0002] A substantial portion of the circuit-board space of conventional radios (e.g., in cellular phones, *etc.*) is occupied by off-chip components (e.g., inductors, capacitors, *etc.*). If all of the components of the radio could be incorporated onto a single chip, the resulting radio would be substantially smaller and more energy efficient than existing radios. To this end, investigators are studying how to create a "single-chip" radio.

[0003] Some proposed architectures for the single-chip radio (and interim architectures) include subsystems that incorporate micro-electromechanical systems ("MEMS") technology. Examples of radio subsystems or "micromechanical circuits" that incorporate MEMS are switches (e.g., for transmit/receive selection; antenna selection, *etc.*), RF and IF filters, signal processors, and tunable oscillators. The MEMS devices that are used in these subsystems function as "circuit elements," and include MEMS resonators, inductors and capacitors. The branch of MEMS technology pertaining to devices for RF applications, such as the single-chip radio, is referred to as "RF MEMS."

[0004] Many of the more useful micromechanical circuits for RF communications are those that include high-Q resonators and microwave and millimeter-wave high-Q filters. As is well known, the "Q" or "quality factor" of a resonator or filter is a measure of its selectivity (among other accepted definitions).

[0005] Possessing a "high" Q is important in oscillators because adequate short- and long-term stability of oscillation frequency is assured only when the Q of the frequency-setting tank circuit exceeds a certain threshold. The ability to implement very selective IF and RF filters is also dependent upon high tank Q. See, e.g., Nguyen et al., "Frequency-Selective MEMS for Miniaturized Low-Power Communication Device," IEEE Trans. Microwave Theory Tech., v(47), no.8, pp. 1486-1503 (Aug 1999).

[0006] MEMS-based resonators have been demonstrated at HF (3 MHz to 30 MHz), VHF (about 30 MHz to 300 MHz) and even UHF (300 MHz to 3 GHz). The

challenge is to maintain an acceptably-high Q at these frequencies. Three types of prior-art MEMS resonators, which are capable of operating at HF or higher frequencies, are discussed below (see FIGs. 1 through 3).

[0007] FIG. 1 depicts "clamped-clamped beam" resonator **100**, which consists of movable beam **102** and stationary drive electrode **108**. Beam **102**, which is electrically conductive, is anchored or "clamped" to underlying ground plane/sense electrode **106** at anchors **104**. Electrode **108** is disposed beneath beam **102**. The beam and electrode are separated by gap **110**.

[0008] Resonator **100** accepts two electrical inputs, v_i and v_p . Electrical input v_p is a DC-bias voltage that is applied to beam **102** via ground plane **106**. This bias voltage generates an electrostatic force that *statically* bends or flexes beam **102** downward toward electrode **108**, reducing the size of gap **110**. It is typically necessary to reduce the size of gap **110** in this fashion since gap **110** is too large as formed to provide adequate electromagnetic coupling for most situations.

[0009] Electrical input v_i is an ac excitation signal that is applied to electrode **108**. The frequency of electrical input v_i is swept, and, in response to certain frequencies, beam **102** vibrates. A current, i_o , is generated by the vibration of beam **102**. This current, which is the output of resonator **100**, is detected directly off the DC-biased ground plane/sense electrode **106**.

[0010] A clamped-clamped resonator having a quality factor of about 8000 at 8.5 MHz resonant frequency (HF) has been demonstrated. See, e.g., Nguyen et al., "Transceiver Front-End Architectures Using Vibrating Micromechanical Signal Processors," cited above.

[0011] Clamped-clamped resonators can be designed for resonant frequencies as high as the UHF range, as a function of material (e.g., polycrystalline silicone, diamond, etc.), vibration mode, and resonator beam dimensions. Furthermore, clamped-clamped resonators are readily fabricated with high stiffness, which is advantageous, because the stiffness of the resonator is proportional to the dynamic range of circuits that include these resonators.

[0012] But the utility of clamped-clamped resonators is limited. This limitation pertains not to operating frequency, but rather to an inability to maintain a suitably high quality factor as operating (resonant) frequency increases. In particular, due to the

relatively high stiffness of most clamped-clamped resonator designs, a substantial portion of internal energy is dissipated through anchors **104** as the resonant frequency approaches the VHF range.

[0013] One solution to this problem is to further miniaturize the dimensions of a clamped-clamped resonator from micron-scale down to submicron or nano-scale. At these smaller dimensions, stiffness can be limited to smaller values to reduce energy loss (to the substrate) through the anchors. But this approach disadvantageously sacrifices power-handling capability or dynamic range, so that it might prove to be unworkable in certain situations, such as for communications applications in which co-site interference is a problem.

[0014] To retain a sufficiently high quality factor at VHF frequencies without sacrificing power-handling capability, a "free-free beam" resonator design was developed. FIG. 2 depicts an example of vertical-mode, free-free resonator **200**.

[0015] Free-free resonator **200** includes movable beam **202** and stationary drive electrode **208**. Beam **202**, which is electrically conductive, is supported at its flexural nodal points **201** by four torsional-mode supports **203**. The remote end (from beam **202**) of each support **203** is anchored or "clamped" to underlying ground plane/sense electrode **206** at anchors **204**. Electrode **208** is disposed beneath beam **202**. Electrode **208** and beam **202** are separated by gap **210**. Beam **202** is biased and excited to resonance in the same fashion as beam **102**.

[0016] Supports **203** have a length that is one-quarter wavelength of the operating (resonant) frequency of resonator **200**. This "quarter-wave" length causes an impedance transformation that advantageously isolates beam **202** from anchors **204**. In other words, beam **202** ideally experiences zero mechanical impedance into its supports **203**, effectively operating as if it were levitated without any supports. As such, the energy-dissipation mechanisms prevailing in clamped-clamped resonators like resonator **100** are substantially suppressed. Consequently, for a similarly-dimensioned resonant structure (*i.e.*, the beam), free-free resonator **200** can attain a relatively higher Q than clamped-clamped resonator **100** at higher frequencies. See, *e.g.*, U.S. Pat. No. 6,249,073; Wang et al., "VHF Free-Free Beam High-Q Micromechanical Resonators," Technical Dig., Int'l IEEE Micro Electro Mechanical Systems Conf., Orlando, FL, pp. 453-458 (Jan 17-21, 1999). And since it is not necessary to reduce the size of beam **202** to

address stiffness considerations (as for clamped-clamped resonator **100**), free-free resonator **200** provides adequate dynamic range and power-handling capabilities.

[0017] Free-free resonators have been demonstrated at frequencies between 30-90 MHz (VHF) with a substantially constant Q that exceeds 8000. See, e.g., U.S. Pat. No. 6,249,073; and Wang et al., "VHF Free-Free Beam High-Q Micromechanical Resonators," cited above.

[0018] While free-free resonator **200** advantageously provides high Q at high frequency, it does have some drawbacks. Some of the key drawbacks of this resonator are related to its vertical mode (*i.e.*, "up and down") of operation. In particular, as a vertical-mode resonator, free-free resonator **200** exhibits:

- Topography-induced frequency uncertainty.
- Lower Q due to larger energy dissipation through anchors **204**.
- Fabrication complexity issues that often constrain vertical mode resonators to be one-port devices, effectively eliminating opportunities for balanced or differential-mode operation.
- Geometric inflexibility imposed by vertical-mode operation.

[0019] The relatively long length of quarter-wave supports **203** is the cause of another drawback of (vertical-mode) resonator **200**. Specifically, due to the relatively long length of quarter-wave supports **203**, resonator **200** is susceptible to "pull-in" or "pull-down." Pull-down is a phenomenon whereby the resonant structure (*i.e.*, beam **202**) is pulled into contact with an underlying structure (*i.e.*, electrode **208**) due to the applied DC-bias voltage. This contact prevents the resonant structure from vibrating. In the case of quarter-wave supports **203**, the application of even a small DC-bias voltage, as is required across between beam **202** and electrode **208** to reduce gap **210** to an acceptably-small size, might cause pull-in.

[0020] To address the drawbacks of the vertical-mode resonator, a lateral-mode, free-free beam resonator was developed. See, e.g., Hsu et al., "Q-Optimized Lateral Free-Free Beam Micromechanical Resonators," Dig. of Tech. Papers, 11th Int'l. Conf. on Solid State Sensors & Actuators (Transducers '01), Munich, Germany, pp. 1110-1113 (June 10-14, 2001).

[0021] FIG. 3 depicts lateral-mode, free-free resonator **300**. As depicted in FIG. 3, resonator **300** includes movable beam **302** and flanking stationary electrodes **308A** and **308B**. Electrode **308A** is a drive electrode (*i.e.*, causes beam **302** to vibrate) and electrode **308B** is a sense electrode (*i.e.*, senses vibration of beam **302**). Each electrode **308** is separated from beam **302** by gap **310**. Beam **302**, which is electrically conductive, is supported at its nodal points **301** by four lateral-flexural-mode supports **303**. The remote end (from beam **302**) of each support **303** is anchored or "clamped" to underlying ground plane/sense electrode **306** at anchors **304**.

[0022] Lateral-mode resonator **300** avoids some of the drawbacks of a vertical-mode resonator, as discussed above. The relatively long length of quarter-wave supports **303** does not render lateral-mode resonator **300** susceptible to pull-in since, under applied DC-bias, the direction of movement of beam **302** is horizontal, not vertical.

[0023] To investigate the degree of isolation provided by (second-mode) supports **303**, the length of supports **303** was varied. Variations from the optimal length of supports **303** (quarter-wave) resulted in a drop in Q (*e.g.*, to about 7000 for a decrease in the length of supports **303** from 25.4 microns to 5.6 microns and to about 4000 for an increase in the length of supports **303** from 25.4 microns to about 31 microns).

[0024] It is apparent, then, that each resonator described above has drawbacks that limit its utility. A need remains, therefore, for an improved resonator design.

Summary of the Disclosure

[0025] The illustrative embodiment of the present invention is a vertical-mode, free-free beam resonator, and micromechanical circuits that include one or more such resonators.

[0026] In resonators and micromechanical circuits in accordance with the illustrative embodiment, the length of each support (which supports the resonating element) is substantially less than one-quarter of a wavelength of the resonant frequency of the resonator. This is in contrast to prior-art, vertical-mode, free-free beam resonators, wherein the length of each support is a full one-quarter of a wavelength of the resonant frequency of the resonator.

[0027] It has been found, unexpectedly, that the quality factor, Q , of vertical-mode, free-free beam resonators in accordance with the illustrative embodiment degrades relatively little as the supports are reduced in length from the usual (quarter-wavelength) length. As a consequence of this reduction in length, resonators and micromechanical circuits in accordance with the illustrative embodiment avoid at least some of the drawbacks of the prior art.

[0028] In particular, free-free beam resonators in accordance with the illustrative embodiment are far less susceptible to pull-in or pull down (of the beam to the underlying electrode) than vertical-mode, free-free beam resonators in the prior art. This is a direct result of the substantially shorter supports of the present resonators.

[0029] In addition to a decreased likelihood of pull-in, this reduction in the size of the supports provides a number of other benefits, including, without limitation:

- an increase in resonant frequency;
- no penalty in power handling capabilities; and
- a decrease in vacuum requirements.

[0030] Regarding the increase in resonant frequency, the decrease in the length of the support contributes mechanical stiffness to the movable beam. By way of example, for a beam having the dimensions 40 microns x 8 microns x 2 microns (length x width x thickness), the resonant frequency increases by about 60 percent (10.4 MHz to 16 MHz) when reducing the length of a quarter-wave support (about 96 microns) down to about 2 microns.

[0031] Since the resonant frequency can be increased without decreasing the size of the beam, power-handling capabilities and dynamic range will not be compromised, as it is for clamped-clamped beam resonators.

[0032] Furthermore, by virtue of its structure, a resonator in accordance with the illustrative embodiment of the present invention can be operated at higher pressure (although still under partial vacuum) than prior-art, clamped-clamped resonators.

[0033] In some embodiments, a resonator in accordance with the illustrative embodiment is capable of passively (no additional power consumption) compensating for temperature-induced or generally-induced (*e.g.*, aging, acceleration, *etc.*) shifts in resonant frequency. This provides temperature stability, such as is needed for reference

oscillator applications in portable wireless communications and for RF channel-select filter banks.

[0034] Compensation is implemented, in some embodiments, using an electrode that overhangs the movable beam of the resonator. The temperature response of the overhanging electrode causes the gap between the overhanging electrode and the beam to increase with increasing temperature. This results in a decrease in the electrical stiffness of the resonator, and a concomitant increase in resonant frequency.

[0035] In some embodiments, this frequency-increase response offsets and cancels the decrease in frequency normally caused by the dependence of Young's modulus on temperature. In some other embodiments, wherein the thermal response of the resonator must satisfy a given profile, rather than be nulled, the overhanging electrode is designed to provide the desired resonance-frequency response with changes in temperature.

[0036] These and other variations of the illustrative embodiment of the present invention are depicted in the Drawings and described further below in the Detailed Description.

Brief Description of the Drawings

[0037] **FIG. 1** depicts a first example of a prior-art micro-mechanical resonator.

[0038] **FIG. 2** depicts a second example of a prior-art micro-mechanical resonator.

[0039] **FIG. 3** depicts a third example of a prior-art micro-mechanical resonator.

[0040] **FIG. 4** depicts a perspective view of a micro-mechanical resonator in accordance with the illustrative embodiment of the present invention.

[0041] **FIG. 5** depicts further detail of a short support of the micro-mechanical resonator of FIG. 4.

[0042] **FIG. 6** depicts a cross-sectional view of the micro-mechanical resonator depicted in FIG. 4 along axis 1-1.

[0043] **FIG. 7** depicts a cross-sectional view of a variation of the resonator of FIGs. 4-6, wherein the resonator provides temperature compensation

[0044] **FIG. 8** depicts a filter in accordance with a variation of the illustrative embodiment of the present invention, wherein two micro-mechanical resonators are coupled.

[0045] **FIG. 9** depicts an oscillator in accordance with a variation of the illustrative embodiment of the present invention.

[0046] **FIG. 10** depicts a first illustrative arrangement for wafer-level vacuum packaging for use in conjunction with the illustrative embodiment of the present invention.

[0047] **FIG. 11A** depicts a top perspective view of a second illustrative arrangement for wafer-level vacuum packaging for use in conjunction with the illustrative embodiment of the present invention.

[0048] **FIG. 11B** depicts a bottom perspective view of the second illustrative arrangement for wafer-level vacuum packaging of FIG. 11A.

[0049] **FIG. 12A** depicts an exploded view of the second illustrative arrangement for wafer-level vacuum packaging of FIG. 11A.

[0050] **FIG. 12B** depicts an exploded view of the second illustrative arrangement for wafer-level vacuum packaging of FIG. 11B.

[0051] **FIG. 13** depicts a cross sectional view of the second illustrative arrangement for wafer-level vacuum packaging of FIGs. 11A-B and 12A-B.

Detailed Description

[0052] The following references provide information that can be used in the design and fabrication of the illustrative embodiments of the present invention. Each of these references is incorporated herein in their entirety:

U.S. Pats. No. 6,249,073 B1, 6,169,321, and 5,976,994.

Publ. U.S. Pat. Apps. US 2002/0070816 A1 and US 2003/0051550 A1.

Nguyen et al., "Micromachined Devices for Wireless Telecommunications," Proc. IEEE, v.(86), no.8, pp. 1756-1768 (Aug 1998).

Wang et al., "VHF Free-Free Beam High-Q Micromechanical Resonators," Technical Dig., Int'l IEEE Micro Electro Mechanical Systems Conf., Orlando, FL, pp. 453-458 (Jan 17-21, 1999).

Nguyen et al., "Frequency-Selective MEMS for Miniaturized Low-Power Communication Device," IEEE Trans. Microwave Theory Tech., v(47), no.8, pp. 1486-1503 (Aug 1999).

Bannon et al., "High Frequency Micromechanical Filters," IEEE J. Solid-State Cir., v(35), n. 4, pp. 512-526 (April 2000).

Nguyen et al., "Transceiver Front-End Architectures Using Vibrating Micromechanical Signal Processors," Dig. Of Papers, Topical Mtg on Silicon Monolithic Integrated Circuits in RF Systems, pp. 23-32 (Sept. 12-14, 2001).

Nguyen, "Vibrating RF MEMS for Low Power Wireless Communications," Proc. 2000 Int'l. MEMS Workshop (iMEMS '01), Singapore, pp. 21-34 (July 2001).

[0053] FIGs. 4 through 6 depict vertical mode, free-free beam resonator **400** in accordance with the illustrative embodiment of the present invention.

[0054] Like resonator **200**, resonator **400** includes movable beam **402** and drive electrode **408**. Beam **402** is electrically conductive, and is advantageously formed of a silicon material, such as polysilicon. Other suitable materials include, without limitation, polydiamond, or plated metals.

[0055] Establishing the resonant frequency of beam **402** is, of course, of major importance in the design of resonator **400**. A variety of parameters affect the resonant frequency of beam **402**, including, for example, its dimensions, stiffness, mass, and beam topography, among others. As a practical matter, the length, l_b , of beam **402** is an important determinant of resonant frequency. For cases in which the length, l_b , of beam **402** is large relative to the width and thickness of beam **402**, the Euler-Bernoulli equation for the fundamental-mode frequency of a free-free beam provides acceptable results. For higher-frequency designs, where the length of beam **402** approaches its width and thickness dimension, a different design procedure (by Timoshenko) is recommended. For the design of free-free beams, such as beam **402**, see U.S. Pat. No. 6,249,073 B1.

[0056] Beam **402** is supported at its flexural, fundamental-mode, nodal points **401** by four torsional-mode supports **403**. Theoretically, there will be no translational movement of beam **402** at nodal points **401**, even when beam **402** is resonating. For further description of fundamental-mode nodal points, including how to determine their position along a beam, see, e.g., U.S. Pat. No. 6,249,073 B1.

[0057] In some other embodiments, less than four torsional-mode supports **403** are used. Exemplary of some of these other embodiments are those in which a plurality of resonators **400** are coupled together to form filters or other complex micromechanical circuits. In some of these embodiments, supports **403** on one side of resonator **400** are replaced by a bridging element that couples two resonant beams **402** together (see, e.g., FIG. 8 and the accompanying description).

[0058] The other end (distal to beam **402**) of each support **403** is anchored or "clamped" to underlying ground plane/sense electrode **406** at anchors **404**. In a departure from prior-art resonator **200**, supports **403** of resonator **400** are not quarter-wave supports. More particularly, supports **403** have a length, l_s , that is advantageously substantially less than one-quarter ($1/4$) wavelength of the resonant frequency of beam **402**.

[0059] It is now appropriate to provide several explanations/definitions. In particular, for use in this specification, the term "length," when referring to the length of a support (e.g., support **403**), means the distance between two "ends" of a support. In the illustrative embodiment depicted in FIG. 5, one end is at the edge of beam **402** and the other end is at anchor **404**.

[0060] It is notable that the phrase "length, l_s , that is advantageously substantially less than one-quarter ($1/4$) wavelength of the resonant frequency of beam" (see para. 0052) references a *length* (i.e., one-quarter wavelength) to a *frequency* (i.e., resonant frequency). But in view of the well-defined relationship between frequency and wavelength ($\lambda = 1/\nu$, wherein λ = wavelength and ν = frequency), the meaning will be clear to those skilled in the art. In particular, it is understood that this phrase means one-quarter of the *wavelength* that corresponds to the resonant frequency (i.e., the "resonant wavelength"). It is conventional, however, to refer to the resonant *frequency*, not a resonant *wavelength*. That convention will be adhered to in this specification.

[0061] In typical vertical-mode, free-free resonators (which will have quarter-wave supports), such as resonator **200**, supports **203** and beam **202** have similar lengths. See, e.g., U.S. Pat. No 6,249,073, Table 1 (col. 9). In contrast, in some embodiments, length, l_s , of support **403** of resonator **400** is less than one-half the length, l_b , of beam **402**. In some further embodiments, length, l_s , of support **403** is less than one-quarter the length, l_b , of beam **402**.

[0062] By way of further quantitative guidance, length, l_s , of support **403** of resonator **400** is not more than about 5 microns in some embodiments, is not more than about 2 microns in some other embodiments, and is not more than about 1 micron and yet some other embodiments.

[0063] Furthermore, in some embodiments in which length, l_s , of support **403** is not more than about 5 microns, the width, w_s , of support **403** is not more than about 2 microns and the thickness, t_s , of support **403** is not more than about 2 microns.

[0064] And in some embodiments in which length, l_s , of support **403** is not more than about 2 microns, the width, w_s , of support **403** is not more than about 2 microns and the thickness, t_s , of support **403** is not more than about 2 microns.

[0065] And in some embodiments in which length, l_s , of support **403** is not more than about 1 micron, the width, w_s , of support **403** is not more than about 2 microns and the thickness, t_s , of support **403** is not more than about 2 microns.

[0066] Furthermore, in some embodiments, length, l_s , of support **403** is equal to width, w_s , of support **403**.

[0067] Electrode **408** is disposed beneath beam **402**. Electrode **408** and beam **402** are separated by gap **410**, as best seen in FIG. 6 (showing underlying substrate **612**). It is to be understood that the term "beneath," used as a descriptor for the position of electrode **408**, is not intended to be used in an absolute sense. In particular, if resonator **400** is "upside down," then, strictly speaking, electrode **408** is "above" beam **402**. It will be understood that terms such as "beneath," "underlying," or the like, when used to describe an orientation of electrode **408** (or other structures), are not meant in an absolute sense.

[0068] Like the prior-art resonators discussed in the Background section, in the illustrative embodiment, resonator **400** accepts two electrical inputs, v_i and v_p .

[0069] Electrical input v_p is a DC-bias voltage that is applied to the electrically-conductive mechanical network (*i.e.*, beam **402** and ground plane **406**). Electrical input v_i is an AC excitation signal that is applied to electrode **408**. A current, i_o , is generated by vibration of beam **102**. This current, which is an output of resonator **400**, is detected directly off the DC-biased ground plane/sense electrode **406**. Of course, other electrical input and output arrangements can suitably be used. For example, in some variations of the illustrative embodiment, resonator **400** has more than two electrical inputs. And in some variations of the illustrative embodiment, resonator **400** has more than one electrical output.

[0070] The electrical impedance into electrode **408** is an important consideration, especially in embodiments in which resonator **400** is used as a filter or in an oscillation circuit. Design considerations pertinent to this issue, including the DC-bias voltage, v_p , the size of gap **410**, *etc.*, are provided in U.S. Pat. No 6,249,073.

[0071] Resonator **400** can be fabricated using standard surface micromachining techniques, in conjunction with, for example, multi-layer (*e.g.*, two-layer, three-layer, *etc.*) polysilicon processes. See, *e.g.*, U.S. Pat. No 6,249,073.

[0072] In some prior-art resonators, such as the resonators described U.S. Pat. No 6,249,073, "dimples" are provided on the bottom of the resonating beam (see dimples **26**). The dimples function as stand-offs as an aid in setting gap spacing and in preventing pull-in, as is likely to occur with the quarter-wave supports that are used for prior art free-free resonators. A resonator in accordance with the illustrative embodiment of the present invention, such as resonator **400**, does not require "dimples" since it is far less susceptible to pull-in than prior art free-free resonators.

[0073] Resonator **400** achieves satisfactory performance in terms of quality factor, operating frequency, dynamic range, power-handling capabilities, and resistance to pull-in. Yet, for certain applications, its thermal stability is unacceptable.

[0074] Young's modulus and stress variations with temperature are believed to have the strongest impact on resonance frequency. Combined, they yield a monotonically decreasing resonance frequency-versus-temperature curve. Although many techniques exist to reduce thermal effects (*e.g.*, temperature compensation circuitry, oven control, *etc.*), they consume significant amounts of power.

[0075] FIG. 7 depicts a cross-sectional view of resonator **500**, which is a variation of resonator **400** that includes a structure that compensates for temperature-induced (or generally-induced) shifts in the resonance frequency of resonator **400**. See, Publ. U.S. Pat. App. US 2003/0051550 A1.

[0076] The structure that compensates for induced-shifts in resonant frequency is overhanging electrode **714**, which bridges beam **402**. Overhanging electrode **714** comprises top electrode **716**, which is supported by members **718**. Top electrode is separated from beam **402** by gap **720**.

[0077] Overhanging electrode **714** is formed from a material that expands faster than the material that comprises beam **402**, supports **403**, and anchors **404**. For embodiments in which beam **402**, supports **403**, and anchors **404** comprise polysilicon, overhanging electrode **714** comprises, without limitation, metal. As a consequence of this selection of materials, the bottom surface of the top electrode **716** moves upward faster than the top surface of beam **402** (the movement of beam **402** is due to the thermal expansion of anchors **404**, supports **403** and the thickness of beam **402**). This results in a net increase in the size of gap **720**. This increase in the size of gap **720** leads to a decrease in the electrical spring constant over capacitive gap **720** and a corresponding increase in the resonance frequency.

[0078] By choosing appropriate values for DC-bias voltage, v_p , and for the size of (initial) gap **720**, the increase in resonant frequency of beam **402** can be tailored to exactly cancel the temperature-induced decrease in resonance frequency. Or, alternatively, overhanging electrode **714** is designed to provide any desired resonance-frequency response with changes in temperature.

[0079] Further disclosure concerning the design of an overhanging electrode for temperature-induced (or generally-induced) shifts in resonant frequency is provided in Publ. U.S. Pat. App. US 2003/0051550 A1. Those skilled in the art will be to apply the teachings of that disclosure to the design of resonator **500**.

[0080] FIG. 8 depicts filter **800** in accordance with a variation of the illustrative embodiment of the present invention, wherein two micro-mechanical resonators **400** are mechanically coupled via link **822**. The two beams **402A** and **402B** function as capacitively-transduced micro-mechanical resonators while line **822** serves as an acoustic transmission line.

[0081] Filter **800** is excited in a manner that is similar to that described for resonator **400**. In particular, a DC-bias voltage, v_p , is applied to the electrically-conductive mechanical network, which in this case includes beams **402A** and **402B** and ground plane **406**. AC excitation signal, v_i , is applied to input electrode **408A**.

[0082] Link **822**, which in FIG. 8 is implemented as a beam, couples energy between resonators **402A** and **402B**. This results in a coupled, two-resonator system with two modes of vibration that define the passband of filter **800**. The center frequency, f_o , of filter **800** is determined primarily by the resonance frequency of resonators **402A** and **402B** (for this illustrative embodiment, resonators **402A** and **402B** are assumed to be identical). The bandwidth of filter **800** is dictated by the relative stiffness of link **822** and resonators **402A** and **402B**. Note that in some embodiments, the resonators **402A** and **402B** are not identical and have a different resonant frequency.

[0083] It is notable that in filter **800**, only two supports **403A** (or **403B**) and two anchors **404A** (or **404B**) are used per beam **402A** (or **402B**). In some other embodiments, a different number of supports (e.g., four, etc.) is used. Furthermore, while a single link **822** is used to couple beams **402A** and **402B**, in some other embodiments, two or more links are used. Also, it is to be understood that in some variations of a filter in accordance with the illustrative embodiment, the filter will have more than two resonators.

[0084] For further details concerning the design and fabrication of filters, which those skilled in the art can suitably apply to the design and implementation of filter **800**, see, e.g., Bannon et al., "High Frequency Micromechanical Filters," IEEE J. Solid-State Cir., v(35), n. 4, pp. 512-526 (April 2000); Nguyen et al., "Micromachined Devices for Wireless Telecommunications," Proc. IEEE, v.(86), no.8, pp. 1756-1768 (Aug 1998), and other publications referenced herein.

[0085] FIG. 9 depicts oscillator **900** in accordance with a variation of the illustrative embodiment of the present invention. Oscillator **800** includes load **924**, which is electrically coupled to negative-resistance device **928**. Load **924** incorporates resonant structure **926**, which comprises one or more resonators in accordance with the illustrative embodiment (e.g., resonator **400**, etc.). Oscillation frequency of oscillator

900 is determined by load **924** (e.g., the resonant frequency of resonant structure **926**, etc.) and terminating circuits (not depicted).

[0086] As used herein, the phrase "negative resistance" is used to describe a process whereby energy is coupled into a resonant structure to sustain RF oscillations. In some embodiments, negative resistance device **926** is a Gunn diode or an IMPATT diode, which is biased to create a negative resistance. In another common oscillator structure, negative resistance device **926** is realized as an amplification device, such as a transresistance amplifier.

[0087] For further details concerning the design and fabrication of oscillators, which those skilled in the art can suitably apply to the design and implementation of oscillator **900**, see, e.g., Nguyen et al., "Frequency-Selective MEMS for Miniaturized Low-Power Communication Device," IEEE Trans. Microwave Theory Tech., v(47), no.8, pp. 1486-1503 (Aug 1999); Nguyen et al., "Transceiver Front-End Architectures Using Vibrating Micromechanical Signal Processors," Dig. Of Papers, Topical Mtg on Silicon Monolithic Integrated Circuits in RF Systems, pp. 23-32 (Sept. 12-14, 2001).

[0088] To reduce the damping of beam **402** that would otherwise occur in air under ambient pressure conditions, the devices described in this specification (e.g., resonator **400**, filter **800**, etc.) will operate under vacuum in the presence of an inert gas (e.g., argon, nitrogen, etc.). FIG. 10 depicts a first illustrative arrangement for wafer-level vacuum packaging for use in conjunction with the illustrative embodiment of the present invention.

[0089] In FIG. 10, various materials layers are disposed on substrate **612**. Layers **1030** are oxide layers, layer **1032** is a nitride layer, and "cross-hatched" layers **1034** comprise polysilicon. Additionally, bond pad **1036**, signal lines **1038**, and bond pads **1040** and **1042** comprise gold. Cap **1044** provides the hermetic seal for resonator **400**. Cap **1044** can be formed of any of a variety of suitable materials, including, without limitation, glass, quartz, or silicon. Thermocompression bonding, well known in the art, is used to attach cap **1044** to the wafer. The thermocompression bond occurs at gold layers **1040** and **1042**.

[0090] An important packaging consideration is how to electrically couple hermetically-sealed resonator **400** with circuits/devices that are outside of the hermetic seal. In the embodiment depicted in FIG. 10, electrical contact is formed by an

"embedded interconnection," shown generally at **1046**. The embedded electrical interconnection is created by polysilicon traces **A**, **B**, and **C**. Trace **B**, which is formed from the "Poly0" layer of the fabrication process, bridges the gap between trace **C** (which is formed from the "Poly1" layer and is disposed within the hermetic seal) and trace **A** (which is formed from the "Poly1" layer and is disposed outside of the hermetic seal).

[0091] FIGs. 11A-11B, 12A-12B, and 13 depict a second illustrative arrangement for wafer-level vacuum packaging for use in conjunction with the illustrative embodiment of the present invention.

[0092] FIGs. 11A and 11B depict perspective views of package **1150**; FIG. 11A depicts a top perspective view and FIG. 11B depicts a bottom perspective view. As shown in those Figures, package **1150** includes cap **1152** and substrate **1156**. Resonator **400** is obscured in FIGs. 11A and 11B; it resides on "top" surface **1258** (see, FIG. 12A) of substrate **1156** within a cavity that is formed by features of cap **1152**, as described below. "Solder" balls **1162** are disposed on "bottom" surface **1160** of substrate **1156** and provide physical and electrical contact to higher-level packaging (not depicted). In some embodiments, cap **1152** is glass and substrate **1154** is silicon.

[0093] FIGs. 12A and 12B provide "exploded" views of package **1150**, wherein FIG. 12A provides the same perspective as FIG. 11A, and FIG. 12B provides the same perspective as FIG. 11B. Resonator **400** is visible in FIG. 12A.

[0094] Disposed on bottom surface **1154** of cap **1152** are a series of concentric squares, identified as inner wall **1264**, middle wall **1266**, and outer wall **1268**. When bottom surface **1254** of cap **1152** is abutted to top surface **1258** of substrate **1156**, inner wall **1264** seals against top surface **1258** to form a cavity (see, FIG. 13, cavity **1376**). Resonator **400** resides within the cavity. In some embodiments, inner wall **1264** and outer wall **1268** comprise a metal.

[0095] Inner wall **1264** defines region **1270**. Getter **1272** is disposed in region **1270**. The getter absorbs gas and moisture. This helps to maintain vacuum in cavity **1376** and prevent condensation on resonator **400**. Getter **1272** can be a single-layer or multi-layer thin film, zirconium-based material, or any other appropriate material, as is commercially available from NanoGetters (Ypsilanti, Michigan), SAES Getters (Viale, Italy) and others.

[0096] Middle wall **1266**, which is disposed in sealing moat **1274** that is formed between inner wall **1264** and outer wall **1268**, comprises a bonding material. The bonding material, which can be, without limitation, a glass frit, solder, *etc.*, is used to bond or other otherwise attach cap **1152** to substrate **1156**. The bonding material is typically heated to effect bonding. Sealing moat **1274** retains any flow that results from heating the bonding material.

[0097] FIG. 13 depicts a cross-section of package **1150**. Some of the features that were previously described that are visible in FIG. 13 include substrate **1156**, cap **1152**, inner wall **1264**, middle wall **1266**, resonator **400**, getter **1272**, and cavity **1376**.

[0098] Additional structures that are depicted in FIG. 13, including front-side contacts **1378**, vias **1380**, and backside contacts **1382**, are used to electrically couple hermetically-sealed resonator **400** with circuits/devices that are outside of the hermetic seal. In some embodiments, there are four vias **1380**: the two that are depicted in FIG. 13, a third that electrically couples to drive electrode **408A**, and a fourth that electrically couples to sense electrode **408B** (the latter two do not appear in the cross-sectional view depicted in FIG. 13). Vias **1380** electrically couple to backside contacts **1382**, which are themselves electrically coupled to solder balls **1162**.

[0099] The dimensions of package **1150** can vary as required. In one embodiment, package **1150** has the following dimensions:

Cavity 1376 :	300 microns (μm) x 300 μm
Thickness of inner wall 1264 :	150 microns μm
Height of inner wall 1264 :	15 microns μm
Width of sealing moat 1274 :	500 microns μm
Thickness of outer wall 1268 :	80 microns μm
Height of outer wall 1268 :	15 microns μm
Substrate 1156 :	1.8 millimeters (mm) x 1.8 mm
Cap 1152 :	1.8 mm x 1.8 mm x .75 mm
Diameter of solder balls 1162 :	0.3 mm

In a second embodiment of package **1150**, the height of inner wall **1264** and outer wall **1268** is 30 microns (other dimensions are the same as in the first embodiment).

[00100] In some embodiments, a post-fabrication annealing operation is conducted. The annealing operation is used, for example, to trim the resonant frequency

and/or enhance the quality factor of a resonator and associated micro-mechanical structures. The annealing operation involves passing a current through the micro-mechanical microstructures of interest (*e.g.*, resonator, *etc.*), thereby heating them. The structures are heated to temperatures that are sufficiently high to change certain micro-structural or materials properties, which results in changes in the resonant frequency and quality factor. See, *e.g.*, U.S. Pats. Nos. 5,976,994 and 6,169,321.

[00101] It is to be understood that the above-described embodiments are merely illustrative of the present invention and that many variations of the above-described embodiments can be devised by those skilled in the art without departing from the scope of the invention. It is therefore intended that such variations be included within the scope of the following claims and their equivalents.